PHONON-PHONON INTERACTION IN CRYSTALS

THIRD QUARTERLY PROGRESS REPORT
1 NOVEMBER 1961 - 31 JANUARY 1962

Signal Corps Contract No. DA-36-039-sc-87209
Order No. 39589-PM-61-91-91
PR and C No. 61-ELP/R-4122

Placed by U.S. Army Signal Research
And Development Laboratory
Fort Monmouth, New Jersey

HEAVY MILITARY ELECTRONICS DEPARTMENT
SYRACUSE · NEW YORK

PHONON-PHONON INTERACTION IN CRYSTALS

Report No. 3
Contract No. DA-36-039-sc-87209
Order No. 39589-PM-61-91-91
PR & C No. 61-ELP/R-4122

Third Quarterly Progress Report
1 November 1961 - 31 January 1962

U. S. Army Signal Research and

Development Laboratory

Fort Monmouth, New Jersey

ELECTRONICS LABORATORY
GENERAL ELECTRIC COMPANY
SYRACUSE, NEW YORK

TABLE OF CONTENTS

LIST OF FIGURES

1. PURPOSE

The work performed under this contract is aimed at studying the generation, propagation and interaction of phonons in solids by means of microwaves. The main interest is centered on phonon-phonon interaction in crystals.

1.1 Task I Analytical Study

Investigate the generation and propagation of phonons in solids. Study the phonon interactions in one and three dimensional media.

1.2 Task II Experimental Study on Phonon Generation and Propagation

Investigate experimental techniques of generating phonons. Develop methods for enhancement of the transducer coupling. Evaluate the properties of phonon propagation in crystals.

1.3 Task III Experimental Study of Phonon Interactions

Study and evaluate the various types of phonon interactions in solids experimentally.

1.4 Task IV Material Evaluation

Measurement of the elastic properties of various materials and search for materials suitable for phonon propagation and interactions.

2. ABSTRACT

The objective of this project is to study the generation, propagation, and interactions of phonons with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

3. PUBLICATIONS, LECTURES, REPORTS, CONFERENCES

Oct. 27, 1961 - "Broad Aspects of the Interaction in Parametric Devices", H. J. Evans & H. Hsu, 1961 IRE-PGED Conference, Washington, D. C.

Nov. 2, 1961 - "Parametric Interactions of Phonons", H. Hsu, Physics Department Colloqium, Syracuse University, Syracuse, N. Y.

Nov. 20, 1961 - Presentation at the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., H. Hsu & S. Wanuga.

Jan. 18, 1962 - "Propagation of Elastic Waves in Crystals", H. Hsu, PGMTT, Syracuse Chapter, Syracuse, N. Y.

4. FACTUAL DATA

4.1 Phase I - Theoretical Aspects

In our first quarterly progress report, we treated phonon interactions as three dimensional parametric interactions and interpreted the particle aspects of these interactions. These concepts are believed to be of fundamental importance to the understanding of many scattering processes. A discussion in this respect is presented in Section 4.1.1.

Phonon interactions are actually a particular case of these three dimensional interactions. One kind of phonon interactions we have not been concerned with so far is the interaction of optical phonons. In Section 4.1.2 some introductory remarks on optical phonon interactions are described.

4.1.1 Three-dimensional Parametric Interactions of Waves and Quasi-particles

The parametric interaction in a cavity can be regarded as point interactions. The investigations of traveling-wave parametric interactions by Tien,[1] among others, extended the understanding to one-dimensional interactions. The purpose of this note is to show that the concept of these parametric interactions can be further generalized to two and three dimensions, and interpreted as scattering of coherent waves or quantised fields of quasi-particles. These concepts apply not only to electromagnetic waves, but also to interactions involving elastic waves, spin waves, plasma waves, etc. As quantised fields, parametric interactions can be interpreted as the annihilation or creation of photons, phonons, magnons, plasmons, etc.

In order to demonstrate the possibility of achieving parametric interaction of traveling waves in three-dimensional media, we choose a moving coordinate system which is moving at an arbitrary velocity $\vec{v}$. Let the frequencies of the original traveling waves be ω_p, ω_i, and ω_s for the pump, idler, and signal, respectively. The corresponding Doppler frequencies in the moving coordinates become ω'_p, ω'_i and ω'_s.

Then

$$\begin{aligned} \omega'_p &= \omega_p - \vec{\beta}_p \cdot \vec{v} \\ \omega'_i &= \omega_i - \vec{\beta}_i \cdot \vec{v} \\ \omega'_s &= \omega_s - \vec{\beta}_s \cdot \vec{v} \end{aligned} \qquad (1)$$

Where $\vec{\beta}_p$, $\vec{\beta}_i$, and $\vec{\beta}_s$ are the phase constants of the three traveling waves. $\vec{\beta}$ and $\vec{v}$ are vector quantities. Parametric interaction becomes possible if the pump frequency is equal to the sum of the idling and signal frequencies, and if the relationship holds for any arbitrary velocity of the moving coordinate system.

That means we have:

$$\omega_p = \omega_i + \omega_s \qquad (2)$$

and require that,

$$\omega'_p = \omega'_i + \omega'_s \qquad (3)$$

From the above three equations, we get

$$\vec{\beta}_p = \vec{\beta}_i + \vec{\beta}_s \qquad (4)$$

Eq. (4) is the condition on the phase constants. Conversely, if Eqs. (2) and (4) hold, Eq. (3) becomes valid and parametric interaction is possible. Thus, Eqs. (2) and (4) are the selection rules to be satisfied for traveling-wave parametric interactions.

For periodic structures such as crystals,[2] Eq. (4) is equivalent to:

$$\vec{\beta}_p = \vec{\beta}_i + \vec{\beta}_s + 2\pi\vec{g} \qquad (4a)$$

where $\vec{g}$ is a lattice vector in the reciprocal lattice. When $\vec{g}$ is not zero, the interaction corresponds to the so-called "umklapp" process in solids.[3]

In the one-dimensional case, the phase constants can be regarded as scalars with either positive or negative signs. Then Eqs. (2) and (4) are reduced to Tien's equations.[1] In a non-linear medium, it is possible to achieve either forward or backward traveling wave parametric amplifications. The significance of the umklapp process has been demonstrated in backward traveling wave parametric amplifiers.[4]

Eqs. (2) and (4) can be expressed as:

$$\hbar\omega_p = \hbar\omega_i + \hbar\omega_s \qquad (5)$$

$$\hbar\vec{\beta}_p = \hbar\vec{\beta}_i + \hbar\vec{\beta}_s \qquad (6)$$

and

$$\hbar\vec{\beta}_p = \hbar\vec{\beta}_i + \hbar\vec{\beta}_s + h\vec{g} \qquad (6a)$$

where $\hbar$ is Planck's constant divided by 2π .

Eqs. (5), (6) and (6a) can be regarded as the particle aspect of traveling wave interactions. Eq. (5) indicates the conservation of energy, Eq. (6) the conservation of momentum, and Eq. (6a) the conservation of crystal momentum. It is expected that Eqs. (5), (6), or (6a) will be satisfied in any scattering processes. Thus, parametric interactions due to scattering of the coherent quantised fields of quasi-particles can conceivably be achieved.

The above discussion can be readily extended to frequency mixing, harmonic generation and parametric interactions involving multiple frequencies.[5] The selection rules, corresponding to the conservation laws, can be generalized as:

$$\sum_i E_i = \sum_s E_s \tag{7}$$

and

$$\sum_i \vec{\beta}_i = \sum_s \vec{\beta}_s \tag{8}$$

or

$$\sum_i \vec{\beta}_i = \sum_s \vec{\beta}_s + 2\pi\vec{g} \tag{8a}$$

where E_i and E_s are the energies of the incident and scattered quasi-particles or traveling waves, $\vec{\beta}_i$ and $\vec{\beta}_s$ are the corresponding phase constants. Eq. (8) applies to continuous media and Eq. (8a), to periodic media. Eqs. (7) and (8a) can be identified as the Bragg Law in the special case of direct scattering involving only one incident wave and one scattered wave.

It should be pointed out that the above selection rules can be calculated quantum mechanically from the interaction Hamiltonian in various collision processes. But the concept of three dimensional parametric interactions was not evident in the formal treatment because the propagation of coherent quantised fields of quasi-particles was not believed possible earlier. With the recent development of the optical maser and the successful propagation of coherent phonons, the concept of three dimensional parametric interaction may become important in the study of solid state physics and quantum field theories. Furthermore, the recent successful generation of optical harmonics utilizing the nonlinearity in the electric susceptibility of piezoelectric crystals,[6] is in fact a demonstration of the three dimensional parametric interaction of coherent photons. Similar parametric interactions should be possible for phonons, magnons, etc. There appears to be an unlimited variety in the potential development of new devices.

4.1.2 Optical Phonon Interactions

The infrared dispersion and absorption of light by the optical mode of crystal vibrations is well known. The absorption is caused by the interaction between the infrared radiation and the dipole moment associated with the lattice vibration of crystals. Rigorous treatments of this phenomena based upon quantum mechanics and the adiabatic approximation are given by Born and Huang[7] and others.

Figure 1 shows the dispersion curves of the lattice vibrations and that of light. The interaction occurs at the frequency where the frequency of the transverse optical mode of lattice vibrations approaches that of the infrared radiation. During the absorption (one phonon-process) a photon of light is annihilated and an optical phonon is created, taking up the energy and momentum of the photon.

This type of interaction is very strong in ionic crystals. For homopolar crystals, such as diamond, silicon and germanium the interaction tends to disappear because the dipole moments of the atoms compensate one another, especially for very long waves. The resulting absorption usually consists of a broad weak band due to the anharmonicity of the lattice vibrations (two-phonon absorption)[8] and a narrow peak which could be explained as due to the dipole moment resulting from the coupling between the displacements and polarization of atoms.[9] For homopolar crystals with different atoms in the unit cell, the dipole moment of the unit cell is not cancelled even for long waves because of the asymmetry of the exchange-dipole forces.[9] Therefore, such compounds

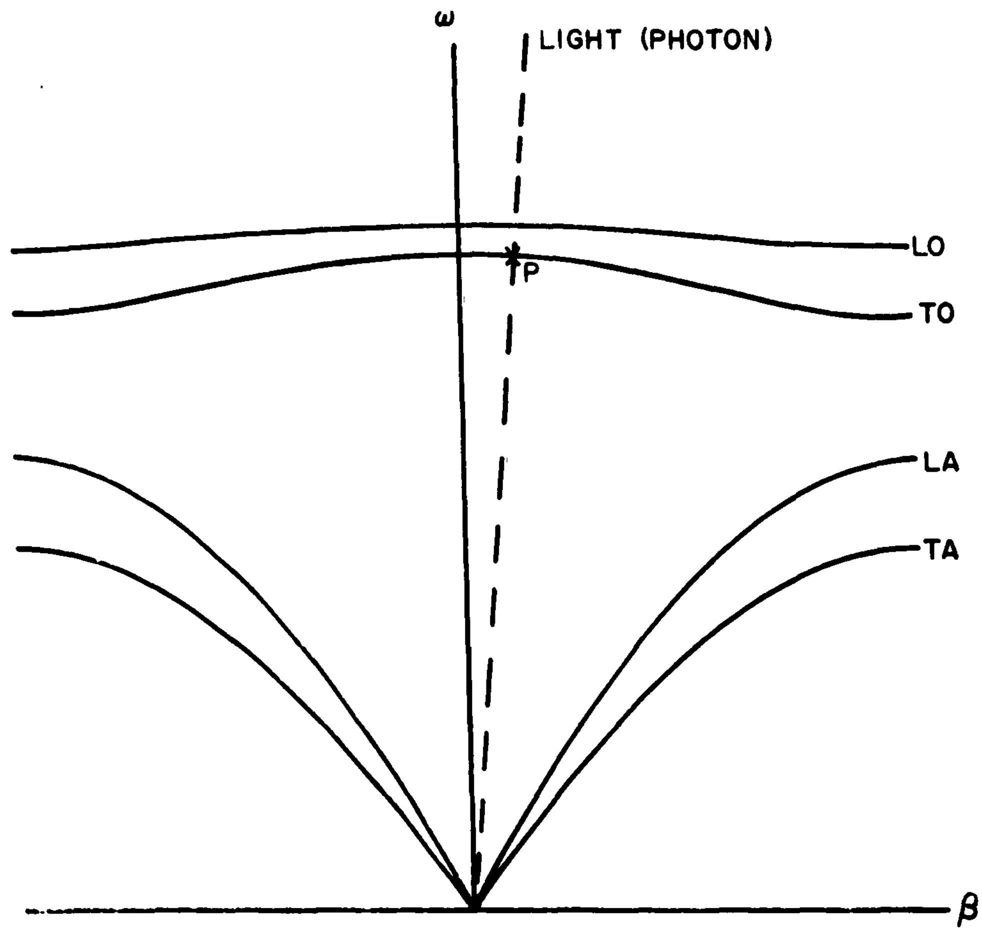


Figure 1. Dispersion Curves of Photons and Phonons Showing Photon-Phonon Coupling at P of Transverse Optical (TO) Phonons.

behave as polar crystals and one-phonon absorption is possible. Infrared dispersion observed for SiC[10] tends to confirm that the one-phonon absorption process could occur also in many semiconductors and is not limited in ionic crystals.

Based upon the theory of infrared absorption of optical phonons, we can expect amplification or generation of infrared radiation if an amplification or oscillation mechanism is introduced to the optical phonons. There are many possible approaches to achieve this property.

Optical phonons have been generated in the tunneling in semiconductor junctions.[11] It is of particular interest that the tunneling process is not only coupled to transverse and longitudinal modes of both acoustic and optical modes, but also to the combination of these various modes. Thus, it is possible to apply the tunneling mechanism not only in the one-phonon process, but also in two-phonon processes. The two-phonon processes would function as parametric interactions.

The photon-phonon coupling serves also as a means of applying optical pumping to phonon-phonon interactions. With an optical maser as a pumping source, it is conceivable that the selection rules for phonon-phonon interactions can be satisfied between the transverse optical phonons and the acoustical phonons. Thus, the energy of incident photons is transformed to phonon energy and serves as a pumping source for amplification of a signal frequency phonon. The interaction is usually a backward traveling wave type of parametric amplification. This kind of interaction is evidently well suited for parametric amplification or mixing of acoustical phonons near infrared freqeuncies. The possible application of an optical maser as the pump in further parametric interactions appears to be another approach which may lead to new devices not only for millimeter or infrared frequencies, but also for optical frequencies.

4.2 Phase II - Experimental Studies

4.2.1 General Considerations

The microwave energy sources used for phonon excitation have been mostly magnetrons with a pulse width of about 1 μsec. and power ratings of 50 watt CW for the S-band frequency and of 1 to 50 kilowatt peak power for the X-band frequency. In the phonon interaction experiments it is desirable to have the pump power large enough in order to induce the anharmonicity of the propagating medium. The effective interaction length when using a pump pulse width of 1 μsec. is too small. New sources of electronically tunable microwave energy supply have been ordered for use as our pump supply in order to increase the power and extend the frequency range of operation. However, some time may elapse until such units arrive and are placed in operation. A surplus unit consisting of a complete supply for mechanically tunable 50 watt CW magnetrons is being modified for use as our pump supply. This supply will be pulse modulated with much wider pulses thereby increasing the pump power. This arrangement is expected to enhance the effective interaction length in the crystal.

Since the available magnetrons are of S-band frequency, various mechanical and equipment changes have been made to incorporate this unit as our pump frequency. New cavities and microwave circuitry are being prepared for the lowering of our operating frequencies for phonon interaction testing. The pump frequency will be in S-band and the signal frequency, L-band.

4.2.2 Complete Cryogenic and Microwave Assembly

During the past period the Microwave Devices Subsection area was relocated to a different part of the laboratory. The new location allows much larger laboratory space and will allow better use of all test equipment and facilities.

Figure 2 shows the complete experimental assembly used mainly with magnetostrictive excitation of phonons. Visible are the 12" Varian electromagnet with a 5" gap, cryogenic Dewar unit, and the auxiliary microwave and electronic components and supplies.

4.2.2.1 Microwave Structures used for Piezoelectric Excitation of Phonons

No completely new structures were designed for piezoelectric excitation. However, cavities for use with our new operating frequencies of S and L band were designed and fabricated. A modified cavity structure containing a new design for enhancing the "E" field was also built and tested.

4.2.2.2 Microwave Structures used for Magnetostrictive Excitation of Phonons

A number of microwave cavities and supporting structures were designed for experimental testing of magnetostrictive phonon excitation at microwave frequencies. Figure 3 shows a complete assembly used mainly for testing various crystals in one helium transfer. This unit incorporates a rod for tuning of the resonant frequency. Visible are the microwave cavity, quartz crystal, coaxial transmission line, tuning rod and flange supporting assembly. Figure 4 shows a closeup of the cavity assembly unit.

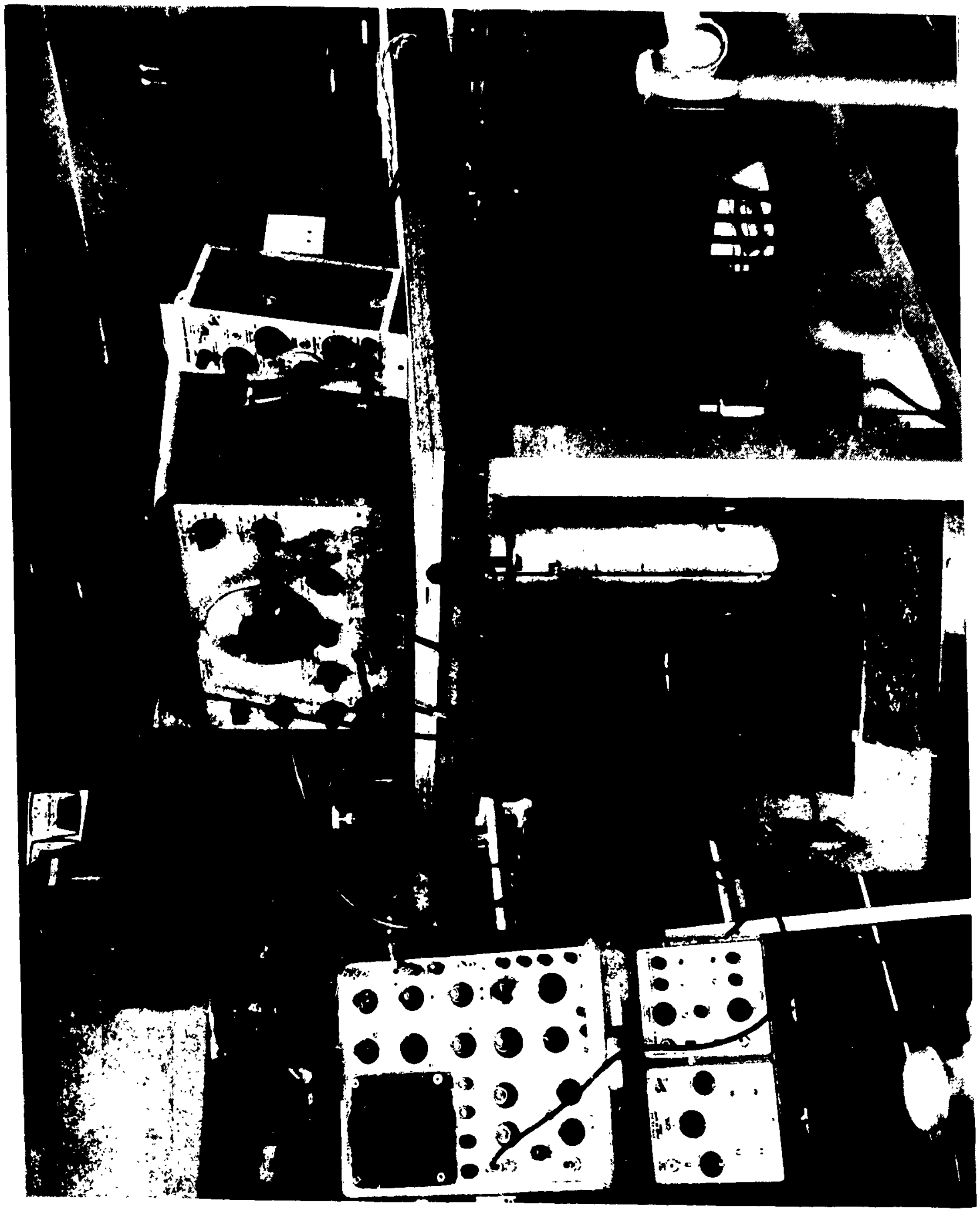


Figure 2. Complete Experimental Assembly for Microwave Phonon Testing Using Magnetostrictive Transducers

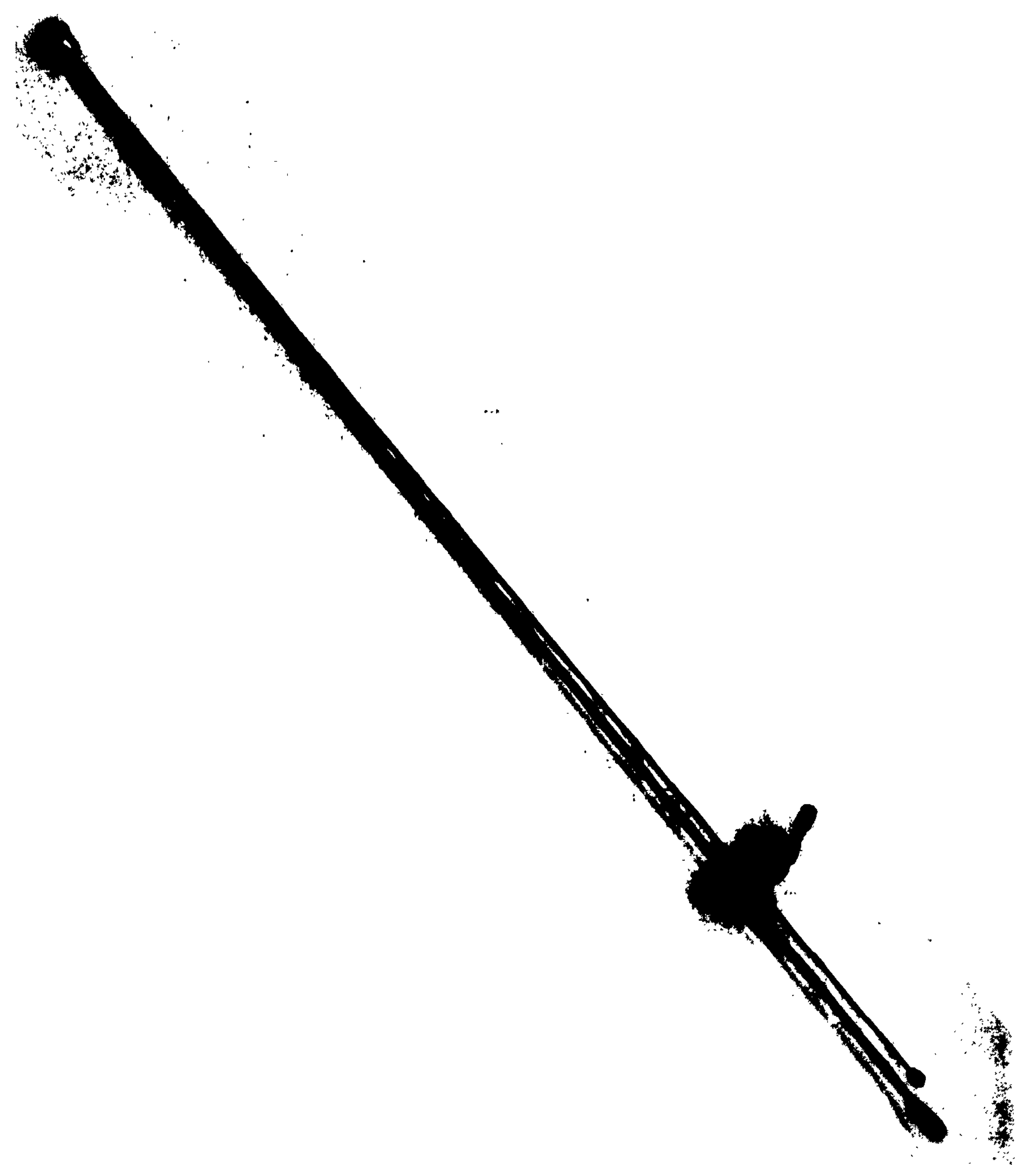


Figure 3. Microwave Structure for Use with Magnetostrictive Excitation of Phonons

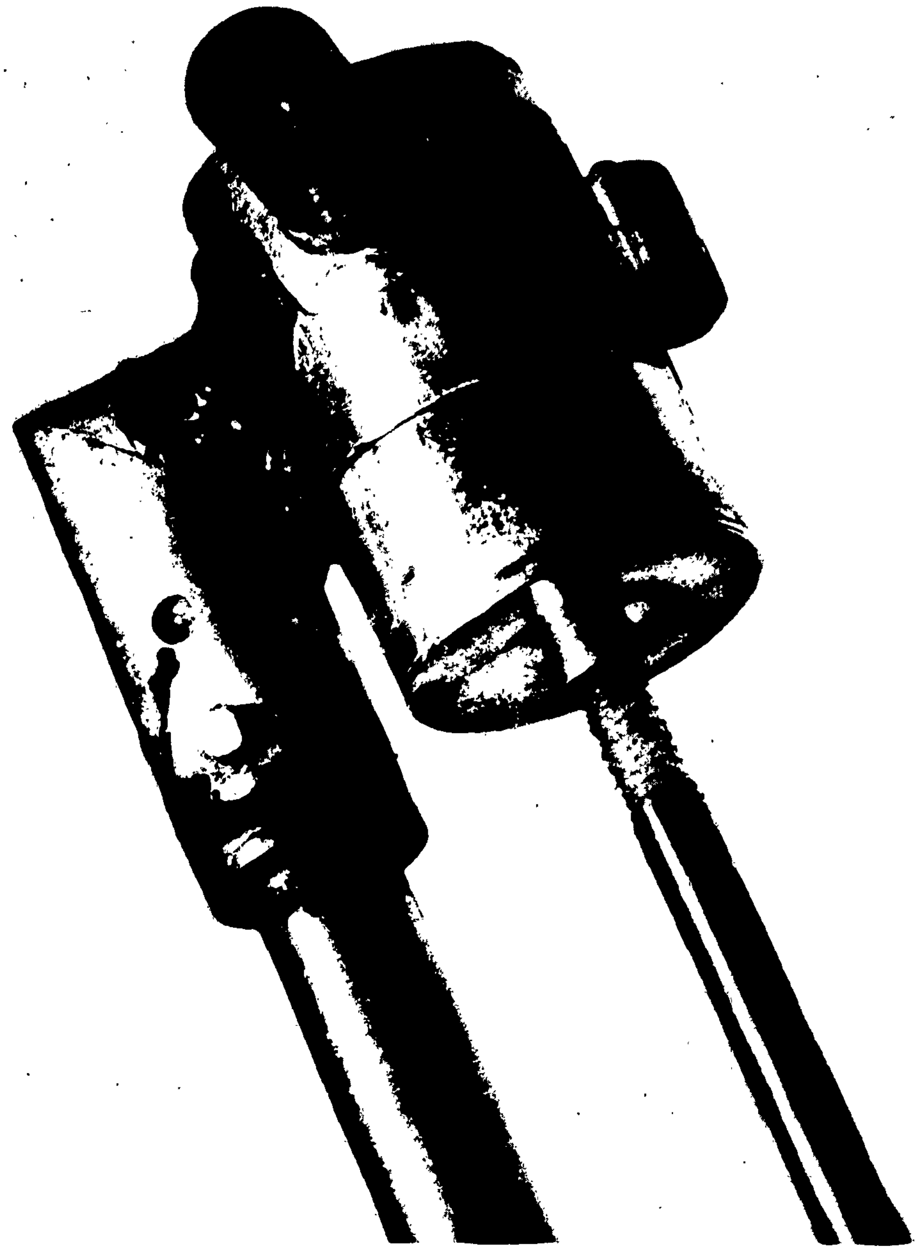


Figure 4. Detailed View of Cavity, Tuning, Crystal and Coaxial Line Shown in Structure of Figure 3

Figure 5 shows a slightly different design used with magnetostrictive phonon excitation. The figure shows the cavity, a ruby crystal and coax transmission line.

A coaxial structure consisting of silver plated stainless steel tubings and terminated by a short was built for wide band excitation of phonons. This structure was made for testing crystals plated with magnetostrictive transducer films.

Additional structures utilizing magnetostrictive excitation for experimental testing of phonon interaction are in the process of being constructed.

4.2.3 Materials

During this period quartz and silicon have been the two materials mostly tested. The silicon was shaped in cylindrical rods, 6 mm. or 3 mm. dia. by 2 cm. length. The characteristics of the silicon were, n type, phosphorus doped 9×10^{13} atoms/cm^3, and resistivity about 78 ohm-cm. One ruby rod that had been used in a laser was also tested using a magnetostrictive transducer.

4.2.4 Experimental Results

4.2.4.1 Generation of Phonons

The results with magnetostrictive excitation of phonons in quartz have been extended to various other mediums. Microwave phonon generation of 3 kMc/s has been observed in numerous silicon crystals and also a

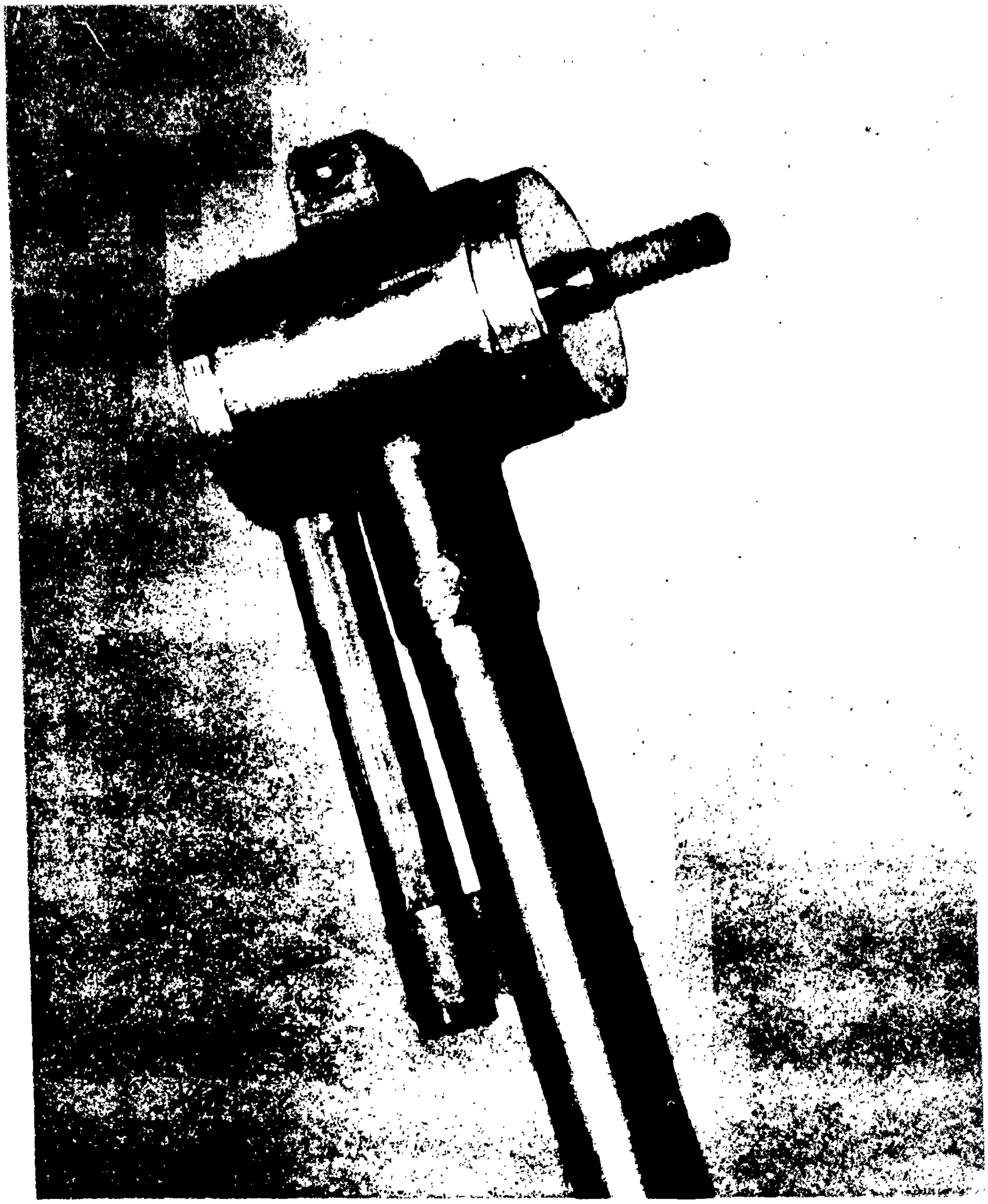


Figure 5. Detailed View of Cavity Structure Used with Magnetostrictive Excitation of Phonons

ruby crystal. This type of transducer has been very successful. The advantage of using a thin magnetostrictive film lies in the fact that the geometry of the propagating medium stands very little chance of being changed. All transducers and propagating mediums require stringent optical tolerances for operating at microwave frequencies. The ends must be optically flat to 1/20 wavelength of light, parallel to 0.001 degrees and normal to the crystal axis to within 0.01 degrees. Any change in flatness or parallelism will deter proper propagation. The film is applied to the flat end surface of the rod. The ends of the rod, thus remain flat and parallel according to their original shape.

The generation of microwave phonons by piezoelectric effect was also studied using thin quartz transducers bonded to silicon rods. The problem of thin acoustic bonding arises using this technique. Several attempts at bonding were made using thin films of vapor deposited or sputtered indium. A thin layer of indium was deposited onto one end face of both the quartz transducer and silicon rod. These two were then bonded under a high compressive force by using a hydraulic jig. The unit was placed in an oven and the temperature was kept just below the melting point of indium for 4 to 6 hours. Although the bonds held, they were mechanically weak and no echoes were observed when the rods were tested at liquid helium temperature. Different materials of more desirable qualities, ie. more mechanical strength, better mechanical impedance match and low loss, are being considered for use with this technique of bonding.

Although both the piezoelectric and magnetostrictive excitation of microwave phonons will still be pursued, it appears that the magnetostrictive type of transducer is favored. The thin films appear to adhere well with no difficult bonding problems. It is also apparent that the efficiency of energy conversion is higher using the magnetostrictive method.

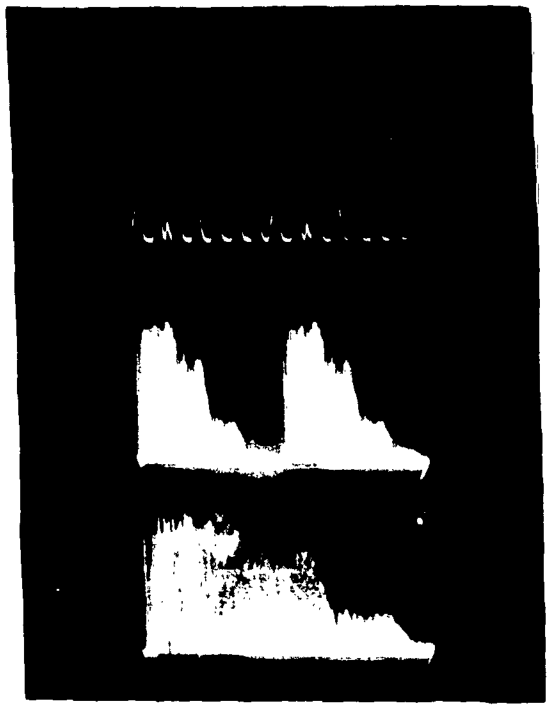
4.2.4.2 Phonon Propagation in Quartz

As stated before, microwave phonon propagation in quartz is still being pursued. Several experiments were carried out at S band frequency and liquid helium temperature using single crystal quartz both as the transducer and propagating medium.

Figure 6 shows better than 2 milliseconds of longitudinal mode storage time in X cut quartz. Our previous maximum was about 1.5 milliseconds storage time for the same quartz crystal. A slight change in the cavity shape accounts for this improvement. The figure shows about 380 longitudinal mode echoes (corresponding to approximately 2.5 milliseconds of storage time).

Figure 7 shows the results obtained in a test for obtaining some values of attenuation in single crystal quartz. The measurements were made at S band frequency and liquid helium temperatures. An attenuation of approximately 0.06 db/cm was measured for the longitudinal mode in an X cut quartz rod, 6 mm. dia. by 2.5 cm. length. A value of approximately 0.01 db/cm was obtained for the slower transverse mode in an X cut quartz rod 6 mm. dia. by 3 cm. length.

Figure 8 shows the pattern of echoes observed in X cut quartz using a modified microwave cavity structure in an attempt to enhance the transverse mode. The transverse mode corresponds to about 6 milliseconds of storage time and is recognized as being exponential in decay.



10 μsec/cm.

.5 millisec/cm.

.2 millisec/cm.

Figure 6. Longitudinal Mode Echoes in X Cut Quartz.
Liquid Helium Temperature and 2.85 kMc/s

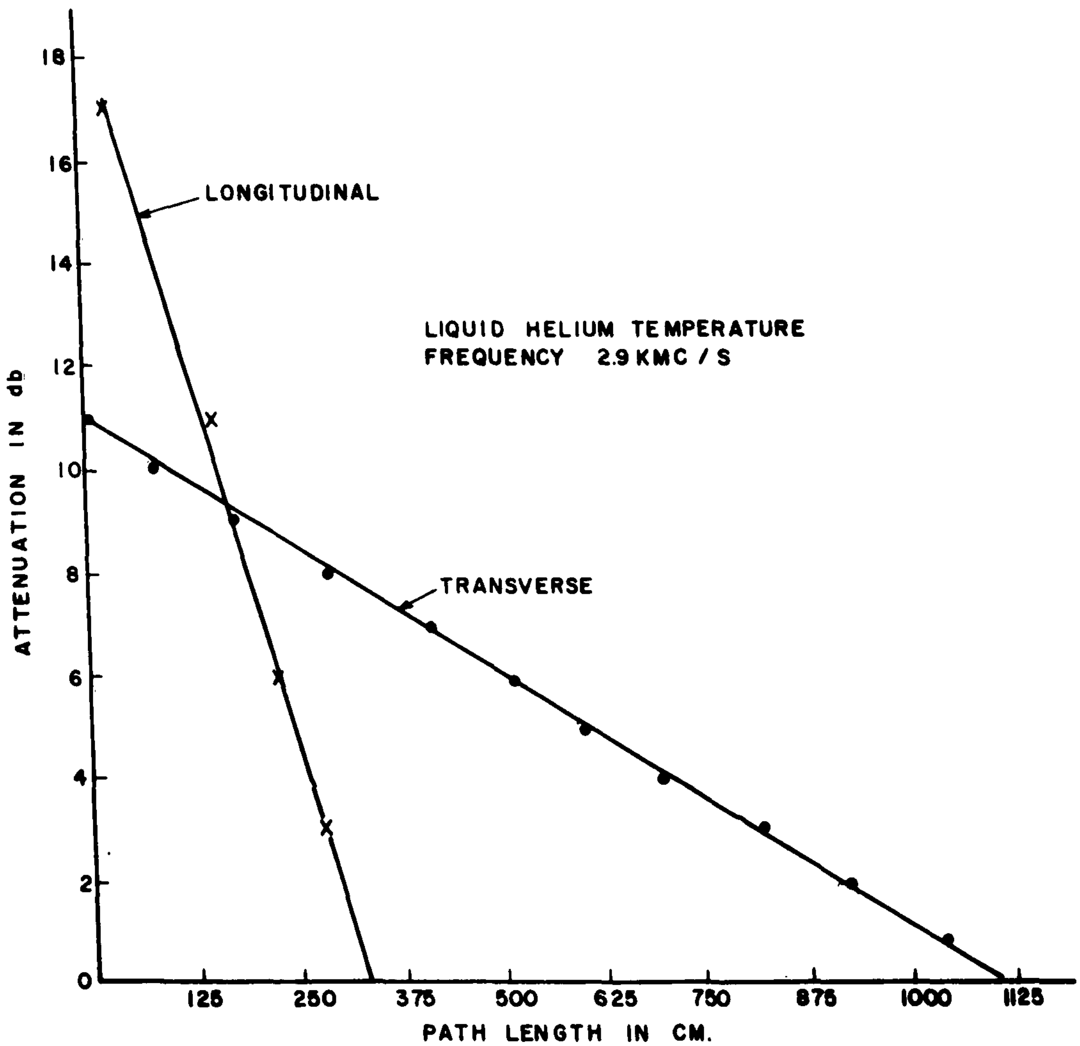
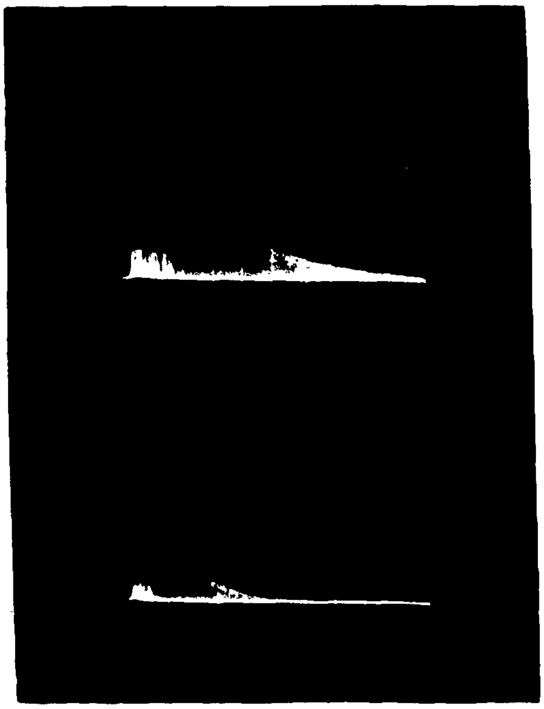


Figure 7. Attenuation in X Cut Quartz
Longitudinal Mode $\approx$0.06 db/cm. (2.5 cm × 6 mm. dia. crystal)
Transverse Mode $\approx$0.01 db/cm. (3.0 cm × 6 mm. dia. crystal)



.5 millisec/cm.

1 millisec/cm.

Figure 8. 3.3 kMc/s Transverse Mode Echoes in X Cut Quartz
Using Enhanced "E" Field Structure

4.2.4.3 Phonon Propagation in Silicon and Germanium

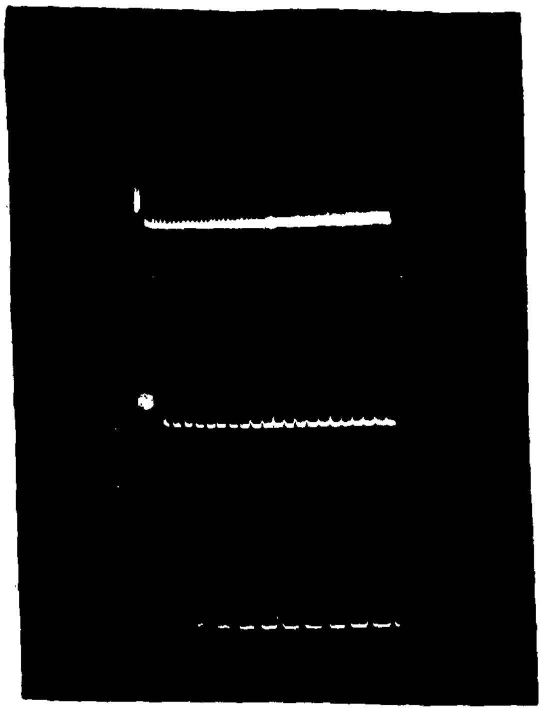
Numerous attempts were made in an attempt to propagate microwave phonons using quartz transducers bonded to silicon. No echoes were observed. It is believed that the fault was in the bond.

We have succeeded in generating S band frequency phonons in both 6 mm. and 3 mm. dia. <111> silicon rods using magnetostrictive transducers. The results have been reproducible and show great promise for use in our phonon interaction testing. No echoes were observed in germanium by magnetostrictive excitation, although we have generated echoes piezoelectrically earlier. The doping level of the germanium may be too high. The germanium material used is n type with antimony doping of 3×10^{14} atoms/cm^3. The resistivity is about 8 oh-cm. The orientation of the germanium crystal is <100>.

4.2.4.4 Technique of Magnetostrictive Excitation

The magnetostrictive films used were of nickel-cobalt composition and were electro-deposited to a thickness comparable to approximately half an acoustic wavelength. The crystal was inserted into a microwave cavity with the end containing the nickel film exposed and arranged parallel to the rf magnetic field. The external DC magnetic field was then applied in various orientations with respect to the film.

Figure 9 shows transverse mode echoes observed in <111> silicon. The test was carried out at liquid helium temperatures and a frequency of 2.67 kMc/s. The veloctiy measured was 5.08×10^5 cm/sec. This agrees quite favorably with our calculated value of 5.12×10^5 cm/sec. as reported in our second quarterly report, page 6. The external DC magnetic field was applied normal to the film for this mode. Figure 10 shows longitudinal

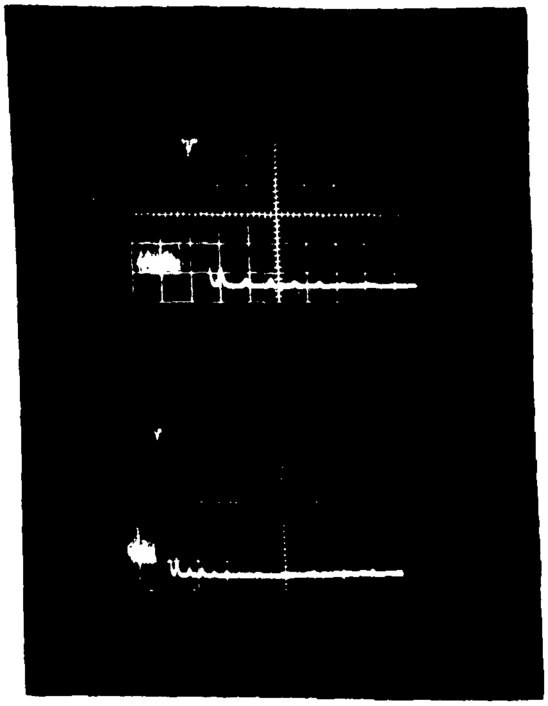


50 μsec/cm.

20 μsec/cm.

10 μsec/cm.

Figure 9. Magnetostrictive Excitation of Transverse Phonons in < 111 > Silicon DC Magnetic Field Normal to Nickel-Cobalt Film. 2.67 kMc/s Liquid Helium Temperature. Velocity is 5.08×10^5 cm/sec.



5 μsec/cm.

10 μsec/cm.

Figure 10. Magnetostrictive Excitation of Longitudinal Phonons in < 111 > Silicon DC Magnetic Field Parallel to Nickel-Cobalt Film. 2.67 kMc/s Liquid Helium Temperature. Velocity is 9.6×10^5 cm/sec.

mode echoes observed in the same < 111> silicon crystal. The DC magnetic field has been rotated to a position that is now parallel with the film. The field strength has also been reduced to 1773 oersted compared with 4500 oersted for the transverse case. The velocity measured was 9.6 x 10^5 cm/sec and compares with our calculated value for this <111> orientation.

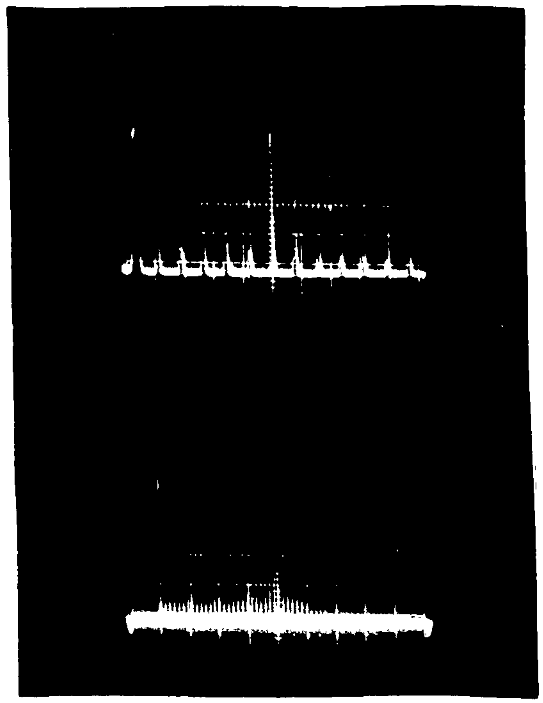
Figure 11 shows the echoes observed for the same <111> silicon crystal under different test conditions. The crystal was completely inserted into the cavity with the film still parallel to the rf magnetic field, but rotated by 90° so that the crystal axis is now parallel with the cavity axis. The DC magnetic field was applied normal to the film and the transverse mode was observed. The coupling appeared to be somewhat stronger for this positioning of the rod.

Figure 12 shows pure longitudinal mode ehcoes observed in <111> silicon crystal 3 mm. dia. by 2 cm. length. The velocity is 9.6 x 10^5 cm/sec.

Figure 13 shows transverse mode echoes in another <111> silicon 6 mm. dia. by 2 cm. length crystal. The film is parrallel to the rf magnetic field and the DC external field is normal to the film.

It is also interesting to consider this case of phonon propagation in the <111> direction since Mason(12) has reported its importance in studying dislocation motion on ultrasonic damping.

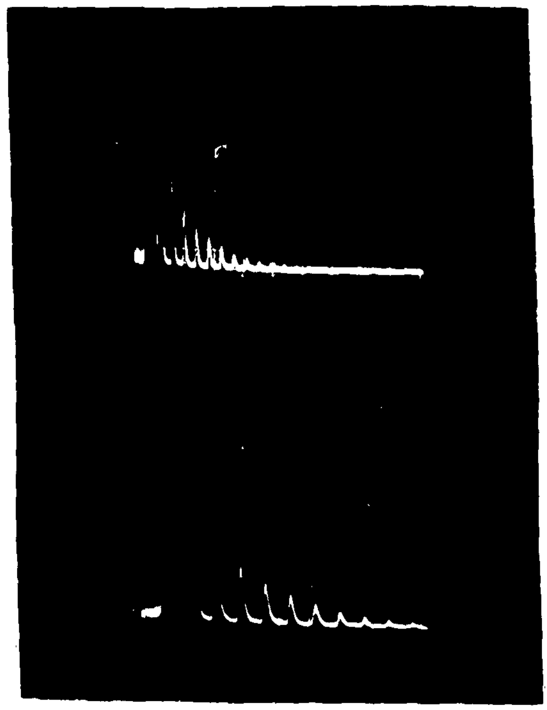
Figure 14 shows echoes observed in a C axis oriented ruby crystal using a nickel-cobalt magnetostrictive film. This ruby had been originally used in an optical maser. There were only a few echoes visible with this rod. It is possible that the optical processing of the rod did not meet our critical tolerances. The test was made at liquid helium temperatures and 3.15 kMc/s. The velocity measured was 11.2 x 10^5 cm/sec., corresponding to the longitudinal mode.



10 μsec/cm.

50 μsec/cm.

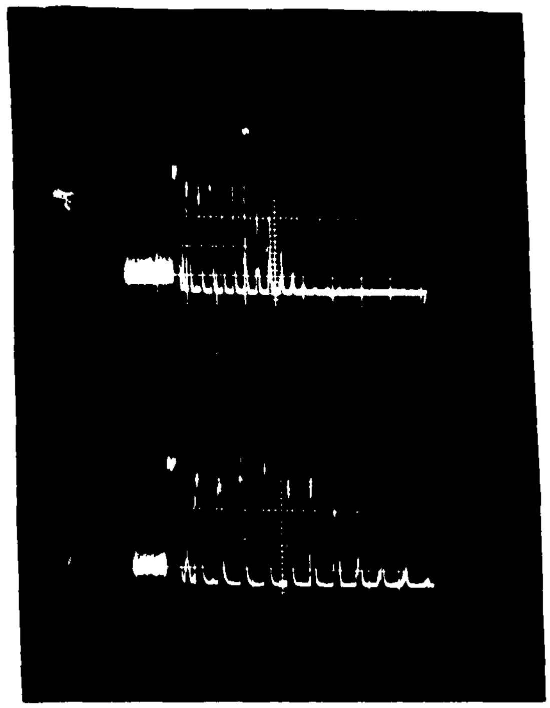
Figure 11. Magnetostrictive Excitation of Transverse Phonons in < 111 > Silicon. Crystal Inserted in Microwave Cavity. DC Magnetic Field Normal to Nickel-Cobalt Film. 2.74 kMc/s Liquid Helium Temperature. Velocity is 5.08×10^5 cm/sec.



10 μsec/cm.

5 μsec/cm.

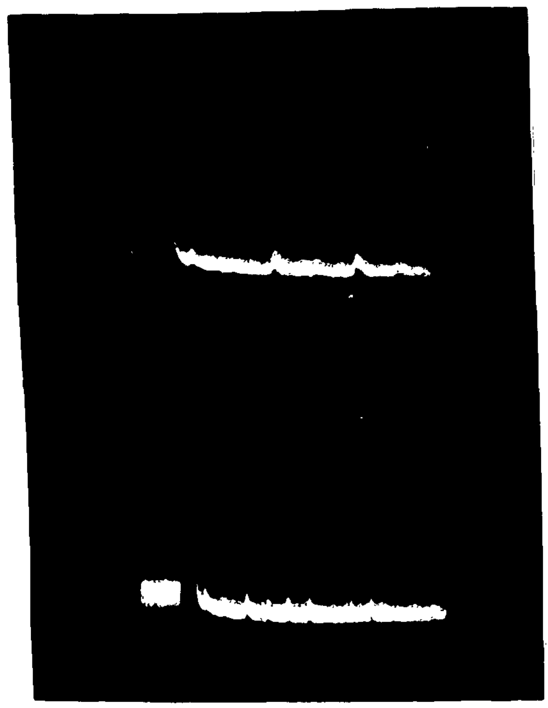
Figure 12. Magnetostrictive Excitation of Longitudinal Phonons in < 111 > 3 mm. dia. By 2 cm. Length Silicon. DC Magnetic Field Parallel to Nickel-Cobalt Film. 3.15 kMc/s Liquid Helium Temperature. Velocity is 9.6×10^5 cm/sec.



20 μsec/cm.

10 μsec/cm.

Figure 13. Magnetostrictive Excitation of Transverse Phonons in Another < 111 > Silicon, DC Magnetic Film Normal to Nickel-Cobalt Film. 2.67 kMc/s Liquid Helium Temperature. Velocity is 5.08×10^5 cm/sec.



5 μsec/cm

10 μsec/cm

Figure 14. Magnetostrictive Excitation of **Longitudinal Phonons** in C Axis Ruby. 3.15 kMc/s **Liquid Helium Temperature.** Velocity is 11.2 $\times$ 10^5 **cm/sec.**

The coupling of magnetostrictive film excitation is largely dependent on the DC magnetic field orientation and field strength. Some of the characteristic behavior observed while experimenting with these thin films is described in the following. With the external DC magnetic field applied normal to the film, transverse waves are generated. Figure 15 shows a plot of the relative magnitude of a particular pulse (the third pulse echo) versus the applied magnetic field strength and magnetic field orientation (angle θ).

These curves were drawn for a thin nickel-cobalt film plated to a <111> silicon rod. In order to obtain the curves in Figure 15, an initial large applied magnetic field (larger than 5000 oersteds) was required to switch the magnetization to the normal direction.

Figure 16 shows a similar plot for the longitudinal mode in a <111> silicon crystal, 3 mm. dia. by 2 cm. length. The film was also nickel-cobalt. For the longitudinal mode there is no need for switching the magnetization.

Comparing Figure 15 with Figure 16, one observes that the longitudinal mode requires lower applied field strength than the transverse mode. The longitudinal mode is not critically dependent on applied magnetic field strength and field orientation as is the transverse mode. Therefore, the longitudinal mode appears more promising for phonon interaction studies. The effects associated with generation and propagation using thin films of magnetostrictive materials are under further investigation.

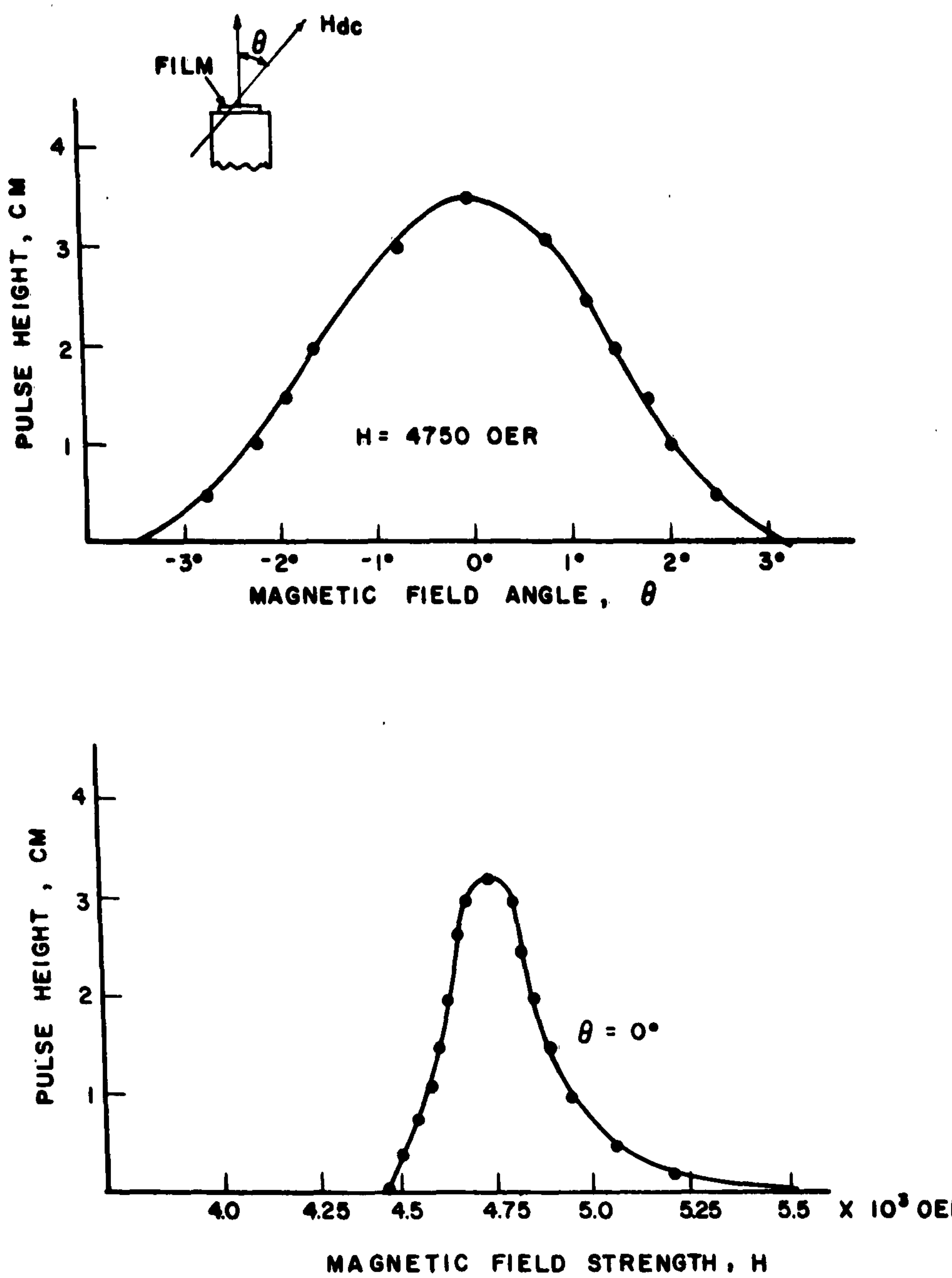


Figure 15. Characteristics of Magnetostrictive Excitation of Transverse Phonons in < 111 > Silicon Frequency. 3.15 kMc/s Liquid Helium Temperature. Velocity is 5.08×10^5 cm/sec.

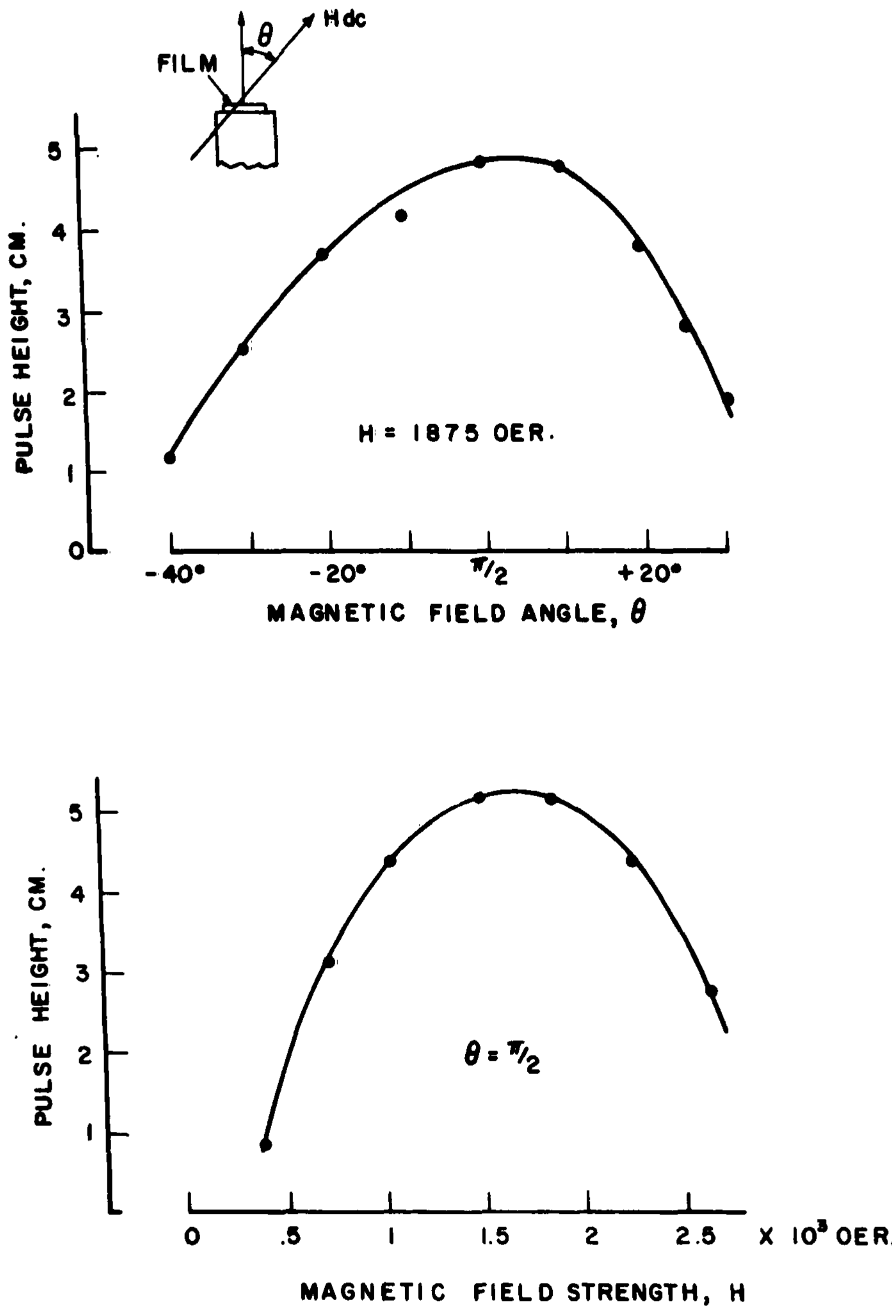


Figure 16. Characteristics of Magnetostrictive Excitation of Longitudinal Phonons in < 111 > Silicon Frequency. 3.15 kMc/s Liquid Helium Temperature. Velocity is 9.6×10^5 cm/sec.

5. CONCLUSIONS

In previous quarterly reports phonon interactions were treated as three dimensional parametric interactions. These concepts apply not only to acoustic and optical phonons, but also to photons, magnons, plasmons, etc.

The results of experimental work on magnetostrictive excitation and detection of microwave phonons are very promising. This technique appears to be particularly useful for non-piezoelectric materials because of the absence of the problem of transducer bonding. Nevertheless, efforts have been continued on the study of thin film bonding of quartz transducers.

Arrangements are being made to expedite earlier experimental testing of phonon interactions.

6. PROGRAM FOR NEXT INTERVAL

Emphasis will be directed towards using the magnetostrictive excitation in various media. Efforts will be made to further investigate magnetostrictive excitations with the purpose of enhancing the transducer efficiency. New microwave circuitry and supplies will be prepared for operating in our new frequency range. Our objectives will then be to concentrate on experimental testing of phonon interactions in both quartz and non-piezoelectric media.

Time permitting, additional bonding films will be attempted with piezoelectric transducers.

IDENTIFICATION OF PERSONNEL

Dr. Hsiung Hsu - 88 hours

Stephen Wanuga - 350 hours

REFERENCES

1. P. K. Tien, "Parametric Amplification and Frequency Mixing in Propagating Circuits," J. Appl. Phys., 29, pp 1347-1357, (September 1958).

2. L. Brillouin, "Wave Propagation in Periodic Structures", Dover Publications, Inc., New York, N. Y., p. 137, (1953).

3. R. E. Peierls, "Quantum Theory of Solids," Oxford University Press, Oxford, England, p. 41, (1955).

4. H. Hsu, "Backward Traveling-Wave Parametric Amplifier", Nachrichtentechnischen Fachberichte, Vol. 22, "Microwave Tubes," pp. 342-345, Verlag Friedr. Vieweg & Sohn, Germany, and Academic Press, New York, (1961).

   H. Hsu and S. Wanuga, "The Wide Tuning Range of Backward Traveling-Wave Parametric Amplifiers", Proc. IRE, Vol. 49, pp. 1339-1340, (August 1961).

5. See, for example; H. Hsu, "Multiple Frequency Parametric Devices", Report of NSIA-ARDC Conference on Molecular Electronics, Washington D.C., pp. 81-85, (1958); Digest of Solid-State Circuits Conference, pp. 12-13, (1959).

6. P. A. Franken, A. E. Hill, C. W. Peters, and G. Weinreich, "Generation of Optical Harmonics, "Physical Review Letters, Vol. 7, No. 4, pp. 118-119, (Aug. 15, 1961).

7. M. Born and K. Huang, "Dynamical Theory of Crystal Lattices," Oxford University Press, (1954).
   V. S. Vinogradov, Sov. Phys. - Solid State, 3, 1249, (1961).

8. M. Lax and E. Burstein, Phys. Rev., 97, 39 (1955).

9. K. B. Tolpygo, Sov. Phys. - Uspekhi, 4, 485, (1961).

10. W. G. Spitzer et al., Phys. Rev., 113, 133, (1959).

11. N. Holonyak et al., Phys. Rev. Letters, 3, 167 (1959).
    R. N. Hall, G. E. Report No. 60-RL-2509G (1960).

12. W. P. Mason "Physical Acoustics and the Properties of Solids," D. Van Nostrand Company, p. 371, (1958).

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanism of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanism of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and Propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-37209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS BY Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanisms of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanisms of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanism of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87200

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanism of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and Propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS BY Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanisms of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanisms of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsuing Hsu and Stephen Wanuga. Second Quarterly Progress Report 1 August 1961 - 31 October 1961. 50 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

Various types of crystals and crystal cuts have been evaluated. With these results, the coupled phonon modes can be calculated from the selection rules for experimental testing of possible phonon interactions. Typical experimental procedures and setups used in experimental testing are described. Experimental results and observations are discussed pertaining to phonon generation in various types of single crystals.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209) Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209) Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209) Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209) Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N.Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. Third Quarterly Progress Report 1 November 1961 - 31 January 1962. 48 pp. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of parametric interactions in scattering processes of waves and quasi-particles is further discussed. Some introductory remarks on interactions of optical phonons are described. Experimental work on the magnetostrictive excitation of microwave phonons in various materials is presented. The results, such as the generation of phonons in silicon, are now reliably reproducible.

UNCLASSIFIED

1. Generation and propagation of hypersonic phonons
2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

UNCLASSIFIED

DISTRIBUTION LIST	No. of Copies
OASD (R&E), Mr 3E1065 The Pentagon Washington 25, D. C. Attn: Technical Library	1
Chief Signal Officer Department of the Army Washington 25, D. C. Attn: SIGRD	1
Director, U. S. Naval Research Laboratory Attn: Code 2027 Washington 25, D. C.	1
Commanding Officer & Director U. S. Navy Electronics Laboratory San Diego 52, California	1
Commander Air Force Command & Control Development Division Attn: CROTL Air Research & Development Command, USAF L. G. Hanscom Field Bedford, Massachusetts	1
Commander Rome Air Development Center Attn: RCOIL-2 Griffiss Air Force Base, New York	1
Commanding Officer Diamond Ordnance Fuze Laboratories Washington 25, D. C. Attn: Library, Rm 211, Bldg 92	1
Commanding Officer 9560 TSU, U. S. Army Signal Electronics Research Unit P. O. Box 205 Mountain View, California	1
Deputy President U. S. Army Security Agency Board Arlington Hall Station Arlington 12, Virginia	1

Distribution List	No. of Copies
Commanding Officer U. S. Army Signal Material Support Agency Attn: SIGMS-ADJ Fort Monmouth, New Jersey	1
Corps of Engineers Liaison Office U.S. Army Signal Research & Development Laboratory Fort Monmouth, New Jersey	1
Marine Corps Liaison Office U. S. Army Signal Research & Development Laboratory Fort Monmouth, New Jersey	1
Commanding Officer Frankford Arsenal Attn: ORDBA-FEL Philadelphia 37, Pennsylvania	1
Chief of Ordnance Attn: ORDTX-AR Washington 25, D. C.	1
Chief, Bureau of Ships Code 691A Department of the Navy Washington 25, D. C.	1
Commander, Army Rocket & Guided Missile Agency Redstone Arsenal, Alabama Attn: Technical Library	1
Director National Security Agency Fort George G. Meade, Maryland Attn: CREF-141 (Room 2C087), Miss Creswell	1
Commander Armed Services Technical Information Agency Arlington Hall Station Arlington 12, Virginia	10
Commander Wright Air Development Division Attn: WCOSI-3 Wright-Patterson Air Force Base, Ohio	2

Distribution List	No. of Copies
Chief, U. S. Army Security Agency Arlington Hall Station Arlington 12, Virginia	2
Advisory Group on Electron Tubes 346 Broadway New York 13, New York	2
Dr. B. Gossick Arizona State University Tempe, Arizona	1
MIT Research Laboratory of Electronics Cambridge 39, Massachusetts Attn: Librarian	1
Lincoln Laboratory MIT P. O. Box 73 Lexington, Massachusetts Attn: R. Kingston	1
Solid State Electronic Laboratory Stanford Electronics Laboratories Stanford University Stanford, California	1
Polytechnic Institute of Brooklyn Microwave Research Institute 55 Johnson Street Brooklyn 1, New York	1
Stanford Research Institute Palo Alto, California Attn: Dr. T. Jones	1
Purdue University Physics Laboratory Lafayette, Indiana Attn: Dr. H. Y. Fan	1
Dr. M. Chodorow Microwave Laboratory W.W. Hansen Laboratories of Physics Stanford University Stanford, California	1

Distribution List	No. of Copies
Director, Electronics Defense Corps Engineering Research Institute University of Michigan Ann Arbor, Michigan	1
Cruft Laboratory Harvard University Cambridge, Massachusetts	1
Mr. Alvin D. Bedrosian USASRDL Liaison Officer SCLO/MIT, 26-131 Cambridge 39, Massachusetts	2
Mr. Lester Gubbins, RASGR Rome Air Development Center Griffiss Air Force Base, N.Y.	1
Commanding Officer U. S. Army Signal Research & Development Laboratory Fort Monmouth, New Jersey	
Attn: Director of Research	1
Attn: Technical Documents Center	1
Attn: Technical Information Division	3
Attn: Rpts Dist. Unit, Solid State & Frequency Control Div. (Record Copy)	1
Attn: Director, Solid State & Frequency Control Division	1
Attn: Ch, S&M Br., Solid State & Frequency Control Div.	1
Attn: Deputy Director, Solid State & Frequency Control Div.	1
Attn: W. G. Matthei, Solid State & Frequency Control Div.	7
Attn: F. A. Brand, Solid State & Frequency Control Div.	1
Attn: H. Mette, Solid State & Frequency Control Div.	1
Attn: Dr. E. Hafner, Solid State & Frequency Control Div.	1
	65